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Title page

Title: Driving speed is altered by monocular ND filters: the Enright phenomenon.

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Abstract.

**Introduction:** An observer, looking sideways from a moving vehicle, while wearing a neutral density filter over one eye, can have a distorted perception of speed, known as the Enright phenomenon. The purpose of this study was to determine how the Enright phenomenon influences driving behaviour.

**Methods**. A geometric model of the Enright phenomenon was developed. Ten young, visually normal, participants (mean age = 25.4 years) were tested on a straight section of a closed driving circuit and instructed to look out of the right side of the vehicle and drive at either 40 Km/h or 60 Km/h under the following binocular viewing conditions: with a 0.9 ND filter over the left eye (leading eye); 0.9 ND filter over the right eye (trailing eye); 0.9 ND filters over both eyes, and with no filters over either eye. The order of filter conditions was randomised and the speed driven recorded for each condition.

**Results.** Speed judgements did not differ significantly between the two baseline conditions (no filters and both eyes filtered) for either speed tested. For the baseline conditions, when subjects were asked to drive at 60 Km/h they matched this speed well ($61 \pm 10.2$ Km/h) but drove significantly faster than requested ($51.6 \pm 9.4$ Km/h) when asked to drive at 40 Km/h. Subjects significantly exceeded baseline speeds by $8.7\pm 5.0$ Km/h, when the trailing eye was filtered and travelled slower than baseline speeds by $3.7\pm 4.6$ Km/h when the leading eye was filtered.

**Conclusions.**

This is the first quantitative study demonstrating how the Enright effect can influence perceptions of driving speed, and demonstrates that monocular filtering of an eye can significantly impact driving speeds, albeit to a lesser extent than predicted by geometric models of the phenomenon.

**Keywords**

Driving, Speed perception, Enright Phenomenon, Pulfrich Phenomenon, Self motion

## Introduction

Enright, in 1970[1], described an interesting and vivid visual motion illusion. A person seated in a moving vehicle, when looking sideways with a neutral density filter positioned over one eye, may perceive that they are travelling at a different speed from their true speed. If the filter is placed over the leading eye (i.e. the eye which is furthest forward in the vehicle), the observer may perceive that their speed of travel has increased relative to the actual speed). If the filter is placed over the trailing eye (i.e. the eye which is closest to the rear of the vehicle) the percept may be that the speed of the observer has decreased. The Enright effect can be quite vivid, especially when the background is leafy, e.g. driving through a wood. Enright explained this phenomenon in terms of a failure of velocity constancy brought about by inaccurate depth perception, in turn brought about by misleading stereopsis cues where an eye has increased latency of visual processing.

Despite its vividness, the original report[1] remains the sole published report of the illusion. Enright described the effect in qualitative terms, but to date no work has described how the Enright effect may influence driving in quantitative terms. We have approached the problem in two ways, first by developing a geometric model of the Enright effect which makes predictions about how inter-ocular latency, true velocity, and pupillary distance (PD) affect the perceived self-velocity of the observer. It should be noted that much of this work has similitude with the work of Spiegler (1983)[2] who developed a geometric model predicting the apparent path and speed of a Pulfrich target moving in a frontoparallel plane and in 1986 described the more general case for objects moving in other directions.[3]

The second approach is empirical: to measure how the Enright effect affects the actual speed at which drivers travel, when they are asked to drive at a given speed.

*Geometric model*

The misperceived depth of a moving object when a luminance reducing filter is placed over one eye was described by Pulfrich[4], and many subsequent researchers[5-11] have described the effect and provided a mathematical basis for it. The effect can also occur spontaneously (without a filter) as a consequence of disease-induced latency in the signal from one eye.[10, 12-13] In addition the Pulfrich effect has been reported to influence where subjects position their cars on the road in driving simulator experiments. [14]

We have illustrated the geometric basis of the Enright effect in Figure 1. If a filter is placed in front of one eye there is an increased latency of processing for the signal passing from eye to brain. To the observer, the apparent position of the image presented to the filtered eye will be some distance $L$ behind the position of the image presented to the unfiltered eye.

This effect occurs if there is a relative motion of an object with respect to an observer. It is usually described for a stationary observer and a moving object, but also applies for stationary objects and a moving observer, as is the case for driving. For the purpose of this paper on real world driving we will assume the observer is moving and $\Delta t$ is positive if the leading eye has a perceptual latency relative to the trailing eye and is negative if the trailing eye has a perceptual latency relative to the leading eye.

If the object is moving at velocity V with respect to the observer, the interocular delay in processing is Δt, PD is the distance between pupils, d is the actual distance from the observer to an object and d' is the perceived distance to an object,

The distance L is given by

$$L = V\Delta t \qquad \text{(Eq 1)}$$

By similar triangles

$$\frac{d' - d}{d'} = \frac{L}{PD} \qquad \text{(Eq 2)}$$

$$\frac{d}{d'} = 1 - \frac{V\Delta t}{PD} \qquad \text{(Eq 3)}$$

This relationship is similar to equations derived by Enright(1970) for misperception of distance, and to standard Pulfrich effect equations. [2] However, Enright (1970) did not derive a quantitative relationship between these variables and misperceived velocity which can be done as follows.

When cues to perceived distance are removed or distorted in some way (e.g. removing stereopsis, decreasing defocus cues to distance or removing depth cues by viewing down a dark tube) then the size of objects can be misperceived. [15] This loss of size constancy is the basis for a number of size illusions e.g. the Ames room.[16] It may also result in distortions of apparent velocity.[17]

If an observer misperceives distance, then they may proportionally misperceive velocity. For perceptual velocity constancy, for a given angular velocity of an object moving across the visual field,  the ratio between apparent velocity V' and real velocity V will be equal to the ratio between d' and d.  Since this ratio is obtained from equation 1 then:

$$V' = \frac{V}{1 - \frac{V\Delta t}{PD}} \qquad \text{(Eq 4)}$$

Spiegler (1983) derived a similar relationship for the apparent velocity of  a Pulfrich target moving in a fronto-parallel plane.[2] Equation 4 describes the apparent velocity of an observer  if the sole cues to depth were based on misjudged stereopsis, and the sole cues to apparent velocity were angular velocity and apparent depth. Figure 2 shows a graph of predictions from equation 4 with perceived velocity plotted against actual velocity for different induced intraocular latencies. However, in a real world environment such a geometric model may not accurately predict velocity perception. In a moving car, many other factors could influence perception of velocity, including auditory factors such as engine noise, road noise, and tactile factors such as road vibration. Also, perception of distance might be heavily influenced by factors apart from stereopsis cues, for example, pictorial cues, such as angular size of known objects and height in field, and linear perspective.

In addition, if the perceptual disparity *L* is nearly the same size as the subject's PD, then (based on this geometric model) apparent velocity will approach infinity, and if L exceeds the subject's PD, the apparent velocity will be in the reverse direction to the actual velocity. Under these conditions, observers may ignore stereopsis cues to distance and thus their velocity perception will be based on other, non-stereoscopic cues.

These additional factors may well influence how the Enright phenomenon affects driving behaviour. This is of some practical importance because driving at a different speed to the surrounding traffic is a significant risk factor for accidents.[18] In the real world setting, the Enright phenomenon might result from any factor which could induce the Pulfrich effect, e.g. mismatched sunglass tints, monocular cataracts, monocular dilatation, and delays induced by optic nerve disease. We decided to quantify the practical implications of the Enright phenomenon by assessing how well subjects could judge their own driving speed in the presence of an induced Enright phenomenon. This was undertaken on a closed driving circuit to provide real world driving conditions.

## *Empirical measurements*

### Participants

Ten young participants (mean age 25.4 ± 5.8 years; range 21-37 years; 6F,4M) were recruited through undergraduate students, research personnel and their friends in the School of Optometry. All participants were licensed drivers, were in good general health and undertook a basic optometric examination consisting of determination of best corrected visual acuity and optical prescription, slit lamp examination, ophthalmoscopy, TNO stereoacuity testing, and FDT visual field testing. All subjects had best corrected visual acuity that was better than 6/6 in each eye (Bailey-Lovie charts)[19-20] and stereoacuity was 60 seconds of arc or better, determined by a random dot TNO stereo test.

The study was conducted in accordance with the requirements of the Queensland University of Technology Human Research Ethics Committee. All participants were given a full explanation of the experimental procedures and written informed consent was obtained, with the option to withdraw from the study at any time.

*Driving Assessment*

The study consisted of a repeated measures design, where speed judgments were made when viewing through four different lens configurations. All testing took place at the closed driver training circuit at Mount Cotton, Queensland Australia, which has been used in numerous previous studies on vision and driving.[21] The road surface was sealed bitumen with normal lane markings. Testing was conducted along a 600 m straight section of the road surface which consists of three lanes of travel. The driver's view through the driver's side window of the vehicle consisted of an open wooded area along the length of the straight section. The tree line was approximately 5 meters from the driver and trees were typically young eucalypts of 5 meters height or taller. All testing was conducted in sunny conditions on a dry road between 9:00am and 4:00pm, but avoiding the effects of sunlight shining directly into the participant's eyes during testing.

Testing was undertaken in a right-hand drive passenger vehicle (the driver sitting on the right-hand side of the car, which is the standard in Australia) with an automatic transmission. Five of the subjects were tested in a 6 cylinder Nissan Maxima and the other five were tested in a 6 cylinder Holden Commodore. Two investigators accompanied each participant, one in the front passenger seat and one in the rear passenger seat to monitor the road ahead while measurements were made. The vehicle's speedometer was masked so that the driver was unable to see the speed they were travelling at, although the investigator in the front seat was still able to easily read the speedometer.

Subjects were allowed to complete a practice and familiarisation trial lap, with no filters in front of the subjects' eyes, during which feedback was provided by the investigator on driving speed. Subjects then were instructed to move into the centre lane on the road, to look out of the driver's (right) side window of the vehicle and either to "drive at 40 Km/h" or to "drive at 60 Km/h". Subjects had control over the accelerator pedal, and the brake during this time. For safety reasons, the front seat investigator held the steering wheel with one hand during testing whenever the subject was looking out of the driver's side window in order to ensure that steering was not compromised when participants were making the speed judgments. Subjects rested their hands on the steering wheel while testing took place. Subjects were asked to report when they judged they were travelling at the instructed speed, and the investigator in the front seat noted the actual speed of the vehicle at that exact moment. Measurements were made well within the length of the straight, and then the car was returned to the start of the straight for the next measurement.

The experiment was performed with the participants wearing modified goggles which consisted of trial frame cells into which trial lenses and the filters could be inserted. Participants undertook the task for four filter conditions: 0.9ND filters over the right eye (trailing eye), the left eye (leading eye), and both eyes, as well as a control condition of normal viewing (no filters). In addition, where required to achieve 6/6 acuity, spectacle lenses were mounted in the trial frame cells.

For each filter condition, two measurements were taken and averaged at each of two speeds, 40 Km/h and 60 Km/h. The presentation order of the filter conditions was randomised for each subject, but all speed measurements for each filter were taken consecutively. After measurements were complete for each filter condition, the vehicle was stopped, and the front seat investigator changed the filter condition.

## Results

Monocular use of the ND filters significantly affected driving speed when subjects looked sideways from the vehicle. This is shown in Figure 3. There was a significant effect of filter condition on speed ($F_{3,27}=18.27$, $p=0.000001$), and this effect was evident for both target speeds of 40 Km/h or 60 Km/h and there was no significant interaction between filter condition and requested speed condition ($F_{3,27}$ =1.43, p=0.256). *Post-hoc* testing demonstrated that subjects drove significantly slower than the control conditions when the filter was placed over the leading eye ($t_9$=2.57, p=0.030) and significantly faster than the control conditions when a filter was placed over the trailing eye ($t_9$=5.44, p=0.0004). Average speed did not differ significantly between the 2 control conditions (i.e. no filters, or both eyes filtered) ($t_9$=0.526, p=0.611).

There was also a significant difference in average velocity dependant on whether subjects were asked to drive at 60 Km/h or 40 Km/h ($F_{1,9}$=111.29, p<0.001) When subjects were asked to travel at 60 Km/h their actual speed did not differ significantly from 60 Km/h under the control conditions (no filter or both eyes filtered) ($t_9$=0.294, p=0.775). However under these control conditions when asked to travel at 40 Km/h subjects drove significantly faster than 40 Km/h; ($t_9$=3.91, p=0.0036)

## Discussion

In this study we investigated how speed judgements were affected when filters were imposed either monocularly or binocularly for speeds of 40 and 60 Km/h. The results demonstrate that participants judge their own speed differently in the presence of a monocular filter imposed on the leading or trailing eye, when they are viewing the surrounding road scene out of the right side of the vehicle.

In the control conditions (both no filter and the binocular filter conditions) subjects' speeds were close to 60 Km/h when asked to travel at 60 Km/h, but subjects substantially underestimated their speed when asked to travel at 40 Km/h. The signed speed limit on most arterial roads in Queensland is 60 Km/h, so good speed matching might be expected based on driver experience. The speed limit on unsigned suburban streets is 50 Km/h in Queensland and drivers may be unused to judging their speed at 40 Km/h. This may account, to some extent, for drivers in the current study under-estimating their speed when asked to travel at 40 Km/h. These results are also consistent with findings from several previous studies that, when tested on the road without view of a speedometer, participants generally underestimate their speed.[22-26] Importantly, this study shows that, during driving, placing monocular filters over subjects' eyes can affect the speed at which subjects drive. Qualitatively, the nature of this effect is similar to that predicted from the geometric model underlying Equation 4: Drivers with a filter placed over the leading eye would be expected to overestimate their own speed, and accordingly drive slower when they try to achieve a given speed. Subjects with a filter over the trailing eye would be expected to underestimate their own speed and accordingly drive faster to achieve the requested speed. This occurred when patients were asked to drive at 60 Km/h and occurred relative to control conditions (No filters, both eyes filtered) when patients were asked to drive at 40 Km/h. Our quantitative results are also in agreement with the qualitative reports by Enright[1] that the apparent increase in speed, with the filter over the leading eye is not as noticeable as the decrease in speed with the filter over the trailing eye.

Enright[1] reported that the velocity distortion was accompanied by an apparent size distortion of objects of known size in the visual field. Our subjects did not report this effect, possibly because the visual environment consisted of trees, which have relatively poor cues to absolute size.

Our quantitative on-road testing shows that drivers misjudge speed by smaller amounts than that predicted from our geometric models of the Enright phenomenon. From the geometric model shown in Figure 2 a latency of 0.5 ms would provide a reasonable, but not perfect, match for the empirical data, and modelling based on a 1 ms delay substantially overestimates the effects obtained. To illustrate this, on Figure 2 we have plotted our mean results for actual speed with the filters on leading and trailing eyes on the x-axis, against the mean baseline speed without filters on the y-axis (apparent speed). In fact, the 0.9 ND filter used in this study would be expected to cause a much larger interocular delay than 1 ms. Previous studies of the Pulfrich phenomenon and other psychophysical techniques (interocular light onset matching) and electrophysiology, indicate that for 0.9ND filters, latency changes would be between 2.5 and 15 ms. [5-6, 27-29] Therefore, the model described by Equation 2 would predict substantially larger speed distortions than were obtained empirically. The differences between the speed discrepancies predicted by the model and those that occurred when actually driving under real road conditions are likely to arise because when making speed judgements, our subjects were influenced by other, non-stereoscopic, factors such as monocular size cues and also engine noise, road noise and vibration, and these cues improved their accuracy of speed judgement. Non-stereoscopic depth cues also affect the magnitude of spontaneous Pulfrich effect which has been observed to be substantially less than predictable VEP latencies in the same patients.[29]

Nevertheless our real world measurements demonstrate that the Enright phenomenon can cause distortions of speed perception that are of statistical and importantly of practical significance. A 9 Km/h increase in speed (with the trailing eye filtered) and 3-4 Km/h decrease in speed (with the leading eye filtered) might pose problems in keeping an appropriate distance from the vehicle in front, in situations when drivers are performing shoulder checks. It is known that differences in velocity between vehicles significantly increase the risk of traffic accidents.[18] While it is unlikely that drivers will drive with a monocular ND filter, it is possible that the delays induced by conduction disorders (e.g. optic atrophy) might mimic conduction delays induced by ND filters [7-8, 10-12, 30-31] or monocular dilation of patients' pupils might result in interocular perceptual delays. There have been previous reports of driving difficulties in patients who experience spontaneous Pulfrich effects,[11] and also in a patient with monocular pupil dilation.[32] Some of these driving difficulties experienced by patients with spontaneous Pulfrich effects, may be a consequence of the associated Enright effect.

It should be noted, however, that looking sideways from a vehicle constitutes a relatively infrequent and short-lived activity for most drivers, typically occurring briefly, prior to changing lanes. For most drivers, it is unlikely that they will view out of the side window long enough to make the speed changes described in the text. It should be noted that velocity changes accompany the Pulfrich effect when objects are moving in other planes apart from the fronto-parallel plane[3]. From the equations of Spiegler (1986)[3] when a subject has their head turned at angles which are oblique to the direction of travel, or when they are facing the direction of travel, some objects in the visual field will appear to move with distorted velocities. Unless the driver's head is turned through large angles, for typical driving speeds and typical inter-ocular latency differences, most of the objects in the visual field will show only small distortions of velocity, with velocity distortions increasing for objects further to the side. For small head turns the apparent velocity distortions at the edges will be disparate with the smaller velocity distortions of objects closer to the car's direction of travel. It can be shown from Spiegler's equations on apparent direction of Pulfrich stimuli[3] that it is only for a 90 degree head turn that theoretical apparent velocity changes will be even across the visual field, and in accord with real world motion, which perhaps explains the vividness of the Enright effect in this head position. However, given that drivers more typically have their heads facing the direction of travel, or oblique to the direction of travel, it may be worth investigating Enright effects for these head positions as part of further research.

## Conclusions

The results of this study are the first quantitative measurements of how the Enright effect influences driving speed in a real world situation. Our results show a significant change in judgments and choice of driving speeds as a consequence of use of ND filters when viewing binocularly out of the side window of a car. However the actual speed changes were smaller than predicted from a theoretical model which relies on stereoscopic cues to depth, suggesting that other visual and non-visual factors also influence speed judgements while driving.

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**Figure legends**

Figure 1. Apparent shift in position of an object, when viewed with a filter placed over one eye, from a moving vehicle. Parameters are represented as follows: d, target distance; V, stimulus velocity; PD, pupillary distance; L, the linear disparity induced by temporal delay in the eye; d', the apparent distance of the target. The eyes are travelling in leftward direction which results in the target moving rightward across their field.

Figure 2. Predictions from the Enright phenomenon geometric model. Apparent speed is plotted against actual speed. Different curves show different induced latencies. Pupillary distance is assumed to be 63 mm. Curves fitted below the diagonal are for filters causing a relative latency in the trailing eye. Curves fitted above the diagonal are for filters causing a relative latency in the leading eye. Experimental data are also shown with open circles denoting the mean values for when subjects were asked travel at 60 Km/h and closed circles denoting mean values for when subjects were asked to travel at 40 Km/h.

Figure 3. The effects of various filter combination on driver speed, when asked to travel at 60 Km/h (upper curve, open circles) and 40 Km/h (lower curve, filled circles). Results shown are mean speeds, averaged across drivers, and the error bars show ± 1 standard error for the mean.

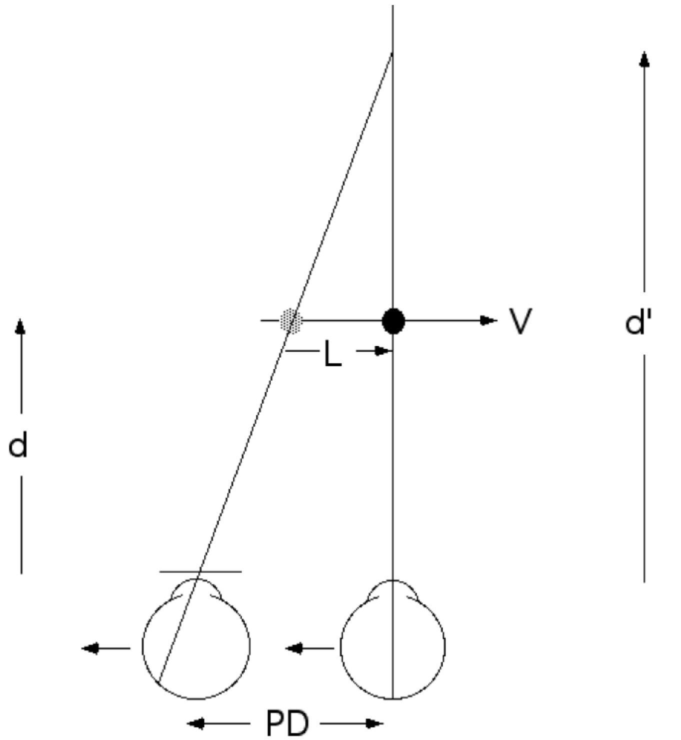
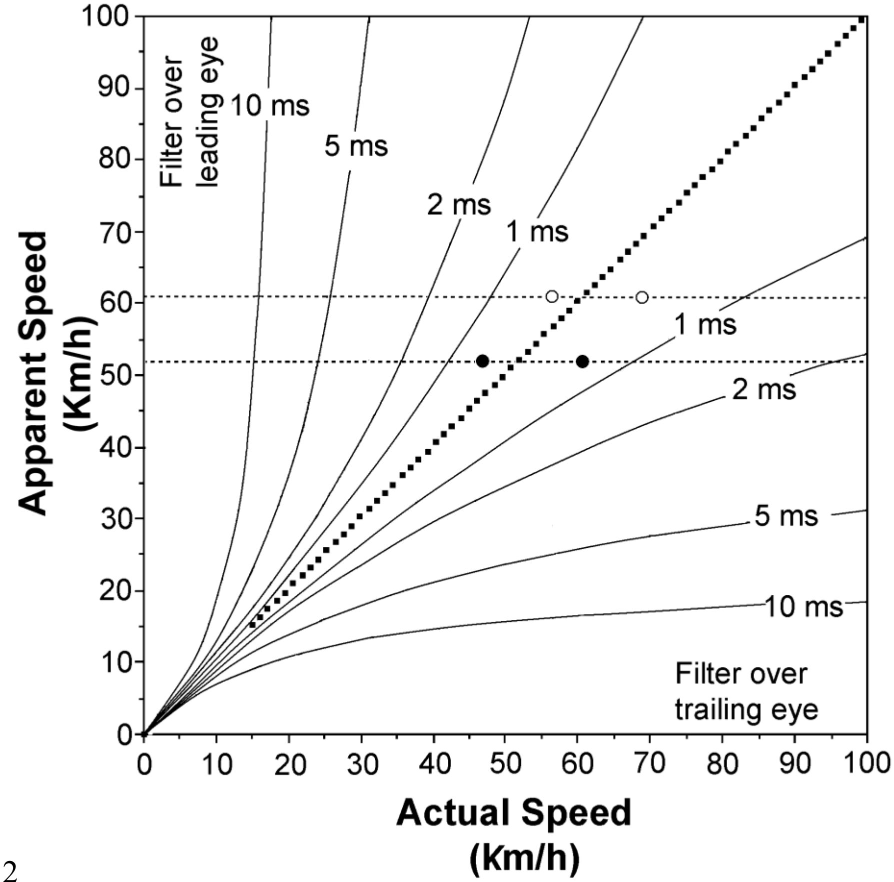
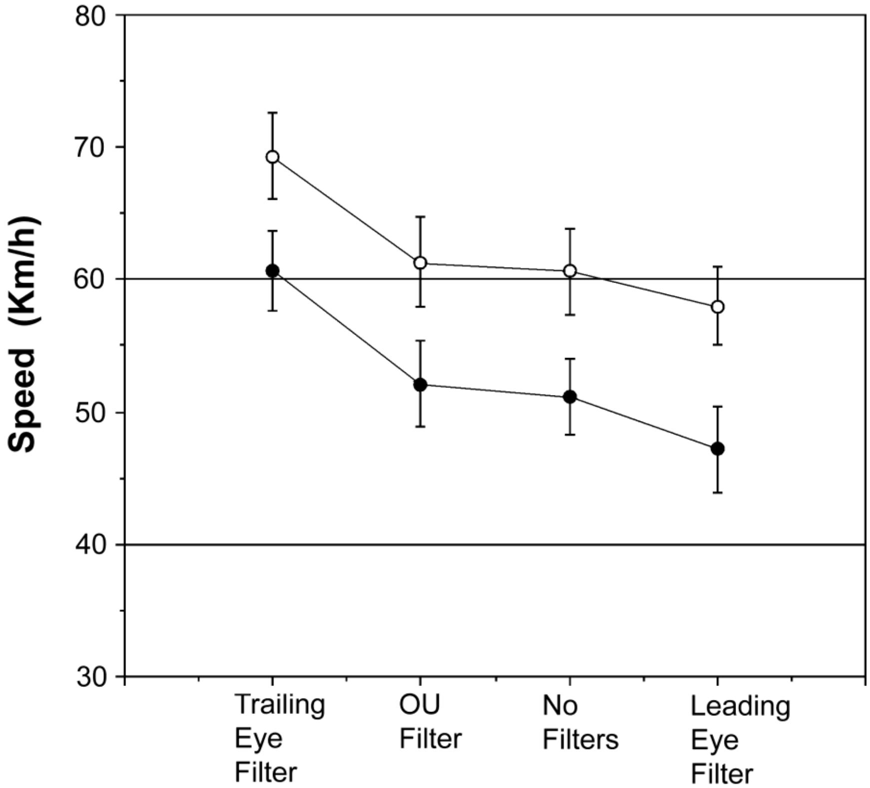



Figure 1.


Filter over leading eye
10 ms
5 ms
2 ms
1 ms
1 ms
2 ms
5 ms
10 ms
Filter over trailing eye
Apparent Speed (Km/h)
Actual Speed (Km/h)
0
10
20
30
40
50
60
70
80
90
100

465 Figure 2




466

467 Figure 3